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JET FUEL DECONTAMINATION STUDIES.

ETHYL CORP FERNDALE MI

JUL 1967

Interim Technical Report No. GR 67-28

JET FUEI DECONTAMINATION STUDIES

July, 1967

Contract No. DA 44-009-AMC-1165(T)

Task No. 1M643324D59209, U. S. Army
Engineer Research and Development Laboratories,
Fort Belvoir, Virginia

Report prepared by

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PREFACE

This study is being undertaken by Ethyl Corporation's Research Laboratories in Detroit, Michigan, on behalf of the U. S. Army Engineer Research and Development Laboratories, Ft. Belvoir, Virginia, under Contract No. DA-44-009-AMC-1165(T).

The contract became effective 10 June 1965 and the termination date is 9 July 1968. The present Interim Report covers the experimental work from 9 January to 10 June 1967.

The Project Engineer for USAERDL is Mr. Edward Russell.

Overall responsibility for the project is in the hands of Dr. E. B. Rifkin, Associate Director, Petroleum Chemicals Research, and Dr. M. E. Gluckstein, Research Supervisor. The work was planned and is supervised by Dr. H. A. Beatty, Research Advisor, and has been carried out principally by Mr. E. Balda.

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SUMMARY

Removal of 0.1% suspended water in JP-5 fuel was measured in a water separometer using a variety of glass, synthetic, and metallic fiber mats at different packing densities. The conditions were such that nearly all the meter readings or "indexes" were below 100, so that the relative effectiveness of the mats could be appraised.

Most of the present work was concerned with the effect of 25 ppm (7 lb/1000 bbl) of Santolene C corrosion inhibitor. This lowers the WSIM of the fuel from 99 ± 1 down to 77 ± 4. All the different mat materials were more or less adversely affected by the surfactant, and there is no expectation of discovering an effective material that is wholly free from this influence. Some materials, like polyester and PVC, strongly adsorb the additive, while others, like Acrilan and nylon do not. This suggests that much of the effect of the surfactant results from lowering of the water-fuel interfacial tension.

However, it was discovered that the adverse action of Santolene C can be wholly or largely overcome by using a 2-layer combination mat, having an upstream layer of fiberglass and a downstream layer of selected material. Thus, a coarse glass mat used alone gave an index of only 40 a particular fibermetal mat had no coalescing action at all (index ≈20); bu the combination of the two gave an index of 100, i. e. complete removal of water. And this combination had a flow resistance less than that of the standard pair of glass mats used to measure WSIM's. This extraordinary synergy offers great possibilities for the development of practicable combinations that will overcome the surfactant problem.

A similar, but much smaller, synergistic action was shown by a downstream layer of sintered polyethylene fiber filter disc. Thus the steel fiber is not unique in this respect. On the other hand, a steel wire cloth and two synthetic fabrics failed to show any benefit.

It has not yet been determined whether similar benefits can be obtained in the presence of other types of surfactants, such as Aerosol OT, or in low-index fuels, such as diesel.

Addition of only 10% of marine diesel fuel to JP-5 lowered the WSIM to 64. Addition of 0.1% antiicer apparently had little or no adverse effect in the few tests made. Increasing the fuel flow rate or water content gave somewhat lower indexes, as expected.

Further work was done on the measurement of capillarity or pore size. A calculated value of the radius of the cells or cages formed by the random array of fibers in a mat gave some correlation with the water-removal index.

Initial steps were taken to make visual and photographic observations of the coalescence process, first on the downstream surface and later, perhaps, in the interior of a mat.

INTRODUCTION

The previous Interim Report GR 67-2 suggested that the structure of a water coalescer mat may well prove to be more important than the nature of the material composing it.

Subsequent work has largely been concentrated on this subject. A wider variety of materials and structures have now been examined. Promising results have been shown by combination mats made of two or more layers of different materials. Preparation of mats made of an intimate mixture of different fibers is far more difficult, and has not yet been undertaken. But this must be done, for it may prove to be advantageous.

The deleterious effect of Santolene C corrosion inhibitor has now been measured for many different materials. A few experiments were also made on the effect of antiicer, and on contamination by diesel fuel.

Further consideration was given to the relationships between packing density, fiber diameter, pore size, fuel flow rate, resistance to flow, and coalescing ability of the mats. A few more measurements of rate of capillary rise were made, and a theoretical paper on pore size in random packings of fibers was studied.

Only a limited amount of effort was spent on further visual and photographic observations. For it now appears that, in proportion to the time required, there may not be much more to be learned from such observations, beyond what we already know from the previous photographic studies at ERDL and in our laboratories.

Nor has any time been spent on the proposed scale-up of the test equipment, since it was felt that this would be premature. This will be done, however, during the coming year, since we now have combinations of materials that are effective on fuel containing Santolene C.

Finally, an effort is being made to follow closely the reports from the several other laboratories who are working in this area.

PART I - EXPERIMENTAL INVESTIGATION

I. MATERIALS

1. Fuels

Capillarity measurements were made with the reference kerosene, Bayol 35, having a viscosity of 2.0 cp, surface tension of 25 dyne/cm, and density of 0.78 at room temperature.

All water separometer runs used additive-free JP-5 from Sun Oil Company; it had a WSIM of 99-100, and this was frequently checked to insure the absence of contamination or oxidation products. Specification antiicer (2-methoxyethanol) and Santolene C corrosion inhibitor was added as indicated.

2. Coalescer Mat Materials

A variety of glass and other fibrous materials were obtained from various sources. These were mostly identified by FM (filter material) code numbers, and those that have already been used are listed in Table 1 below. The metal specimens obtained from Huyck Metals already carried an FM ("Fibermetal") number and these were retained for our list.

The two kinds of calibrated glass discs furnished for routine use in the separometer served as a standard. The "Commercial A" materials are samples of fine and coarse resin-coated glass wool that are used in the manufacture of a commercial filter/coalescer element. Large bats of these were lightly compressed on a tray and cured in the oven, through the courtesy of the manufacturer of the elements. The "Commercial B" materials were taken directly from unused commercial elements from three different sources, and were thus representative of the conditions of actual use.

TABLE 1

COALESCER MAT MATERIALS

Non-metallic

Composition	FM No.	Structure	Fiber diam. μ	Source
Glass, uncoated	1	wool	3-8	Owens-Corning
Glass, resin coated				
Uncured	2	wool	3-20	"
Standard WS coarse	-	"	5-20	Emcee Elect.
fine	-	"		"
Commercial A coarse	3	"	6-24	mfg. of element
fine	4	"	1-5	"
B-1 coarse	-	"	6-24	coml. element
B-2 coarse	-	"	3-40	"
fine	-	"	1-5	"
B-3 coarse	-	"	3-15	"
Acrilan 1656	46	wool	25	Chemstrand
158B	47	"	5-20	"
needle punched	48	fabric	3 + 5	"
Cotton	5	wool	15-40	--
Nylon 0555 SA	8	monofil.	125	DuPont
--	9	"	25	Chemstrand
--	11	"	50	"
1409-53-7	12	felt	--	DuPont
1770-8-B	16	fabric	--	"
1840-15-3	19	"	--	"
-6	21	"	--	"
-7	22	"	--	"
--	49	monofil.	10-14	Chemstrand
Polyester Style 240	43	paper	--	DuPont
340	44	"	--	"
K9001	45	wool	15	Chemstrand
Dacron 54	56	"	45	DuPont
Polyethylene --	6	monofil.	275	Dawbarn
--	54	fiber sheet	--	F. B. Wright
No. 1250	55	disc	--	Bel-Art
Polyurethane 100-pore 1/16	52	foam	--	Foamade
1/32	53	"	--	"
Polyvinylchloride	24	roving	10	Teijin
	25	staple	--	"
	26	wool	37-40	"
	29	fabric	--	"
	38	wool	--	"
	39	fabric	--	"

TABLE 1 - Continued

Metallic

FM No.	Composition	Thickness in.	Mfg. Spec. % voids	Mfg. Spec. med. pore size μ	Obsvd. P cm	Source
232	347 st. steel wire cloth	--	--	--	18.3	Mich. Wire Cloth
236	304 st. steel wool	--	--	--	--	"
123	347 st. steel sheet	1/25	35	85	3.7	Huyck Metals
225	" "	1/16	80	20	64	"
250	" "	1/10	78	40	6.8	"
627	" "	1/25	55	14	21.0	"
1102	302 st. steel sheet	1/16	80	27	16.6	"
1307	430 " "	1/8	80	235	1.2	"
131	Nickel sheet	1	82	60	10.1	"
901	Copper on steel sheet	1/2	80	530	0.5	"
1006	Copper	1/8	80	46	1.0	"

II. INDEX OF DIFFERENT MATS WITH CLEAR JP-5

1. Foreword

In the previous Interim Report, GR-67-2, Tables 6 and 7 gave separometer meter readings for a number of coalescer mats of glass and a few other media. For convenience, these meter readings will now be referred to as the "index" of a mat-fuel system. The term WSIM is reserved for the readings obtained when using the standard combination of fine plus coarse glass discs that is specified for the separometer.

WSIM values are notoriously of low precision. We now have sufficient experience to show that our measurements are more reproducible than might be expected. Values of 95-100 are good to ± 1 unit; at the level of about 75-80, the variation is ± 4; at about 40, it may be as great as ± 10.

At one point in the investigation, the indexes of standard mats with clear JP-5 dropped abruptly. The WSIM fell from 99-100 to about 95, and the index for 2 Standard WS coarse discs fell from 78 ± 4 down to 53 ± 15 in 12 runs. After a lengthy and tedious search, the trouble was (apparently) traced to a small piece of tramp plastic that had become lodged in the outlet line from the fuel reservoir -- at least when this obstruction was removed, the standard ratings at once returned to normal and stayed there. This episode emphasizes the importance of frequent check runs on the machine.

Since the previous report, many additional indexes have now been obtained. The entire group of these data is collected together here, in the following tables. The weights and pressure drops of the mats are also given. The pressure drops are in centimeters of water for an air flow rate of 8 lit/min (as is used

to validate the Standard WS discs). All mats were 1/16 in. thick, except as noted in the tables. Where greater thickness was required, the depth of the coalescer cell was increased by spacers. The materials used are mostly designated by an FM (filter material) number; they are described in Table 1 above.

All the runs listed here in Section II were made with clear JP-5 containing 0.1% water at a flow rate of 150 ml/min in the modified separometer cell. The effect of Santolene C is reported in Section III, and miscellaneous experiments involving other variables are given in Section IV.

2. Glass Mats

Table 2 gives the results for various glass mats, alone or in combination. In all combination mats, the components are given in order of their location, from upstream to downstream. When replicate runs were made and the data were averaged, this is indicated in the last column.

3. Plastic Mats

Table 3 gives the data for the different polymeric materials, including cotton, and for a few combinations of two different layers. Data from Table 5 below on washed mats (previously used for fuel containing Santolene C) are also included, if the indexes were no lower.

4. Metallic Mats

Table 4 lists the results obtained on individual metallic specimens, identified in Table 1. Combinations of these with glass and plastic mats were all tested in the presence of Santolene C, as described below in Table 6.

TABLE 2

INDEXES OF GLASS MATS

Material	FM No.	Wt. mg	ΔP cm	Index	No. of runs
Fine fibers					
0.4 Standard WS	--	18	5.9	48	
1 "	--	42	17.0	82	2
2 "	--	88	52.5	93	
Coml. A	4	30	7.2	57	
"	4	60	--	80	
Coml. B-2	--	13	2.3	37	
"	--	23	7.1	64	
Coarse fibers					
1 Standard WS	--	85	2.1	73	3
2 "	--	170	5.9	78	8
Uncoated	1	142	7.3	66	2
Uncured resin coated	2	255	6.7	50	2
Coml. A	3	301	7.0	86	
Coml. B1	--	219	5.6	83	
Coml. B2	--	253	6.8	67	
Coml. B3	--	136	5.8	85	
Combination of 2 layers					
Standard WS fine + coarse	--	15 + 33	5.2	91	
" coarse + fine	--	36 + 14	5.7	75	
" fine + coarse	--	45 + 84	29.3	99+	14
Coml. A fine + coarse	4 + 3	23 + 38	6.5	98	2
" coarse + fine	3 + 4	38 + 23	5.6	58	
" fine + coarse	4 + 3	46 + 38	15.6	100	
" "	4 + 3	45 + 41	13.0	82	2
" "	4 + 3	47 + 201	38.5	89	
" "	4 + 3	64 + 149	46.2	91	
" "	4 + 3	30 + 300	--	73	
" "	4 + 3	60 + 300	--	72	
Coml. B-2 "	--	18 + 59	6.9	93	
" "	--	12 + 101	8.3	85	

TABLE 3

INDEXES OF PLASTIC MATS

Material	FM No.	Wt. mg	ΔP cm	Index	No. of runs
Acrilan					
Wool 2 den.	46	137	7.5	49	
Wool micro den.	47	72	6.4	48	2
Punched fabric	48	338	6.9	36	2
Cotton					
Wool	5	150	6.4	60	
Nylon					
Bundle of filaments	8	550	62	31	
Chopped filaments	9	254	13.5	31	
Felt	12	166	4.4	35	
Cloth	16	91	57	38	2
Cloth, loose weave	19	402	7.3	45	
Cloth, close weave	21	271	7.1	69	2
Cloth, heavy	22	458	16.9	35	
Wool	49	106	7.3	35	
Polyester					
Paper	43	229	6.6	73	
Paper	44	311	7.0	65	
Wool	45	136	6.4	78	2
Dacron staple 15 den.	56	488	7.9	46	2
Polyethylene					
Bundle of filaments	6	522	80	37	
Sintered fiber disc	55	610	19.6	25	
Polyurethane					
Foam, 100-pore, 3/32 in.	53	305	6.4	36	2
Polyvinylchloride					
Roving	24	527	5.5	53	
Staple	25	184	5.9	57	
Wool	26	261	6.0	54	
Cloth	29	412	40	62	
Wool	38	227	7.0	47	
Cloth	39	435	6.9	23	
Combinations					
Nylon filaments	8 + 11	328	5.3	25	
Nylon cloth + wool	21 + 49	259 + 88	18.4	42	
Polyurethane foams	53 + 52	716	46	42	
2 St. WS coarse glass + PVC FM 29		124 + 407	56	99	

TABLE 4

INDEXES OF METALLIC MATS

Material	FM No.	Inch Thick	Wt. mg	ΔP cm	Index	No. of runs
Steel wire cloth, thin sheet	232	--	219	18.3	19	2
Steel wool, 10 μ	236	1/16	463	6.0	37	
Steel fiber sheet	123	1/25	2596	3.7	19	
	225	1/10	1950	64	83	2
	250	1/10	1928	6.8	21	
	627	1/25	1866	21.0	22	
	1102	1/16	1798	16.6	28	
	1307	1/8	2432	1.2	17	
Nickel fiber sheet	131	1	964	22.6	32	
Copper fiber sheet	901	1/2	3777	0.5	20	
	1006	1/2	4790	2.0	21	

III. EFFECT OF SANTOLENE C CORROSION INHIBITOR

1. Glass and Plastics

An extended series of separometer runs was made to establish the effect of Santolene C on glass and other filter media. Our previous studies on various single fibers had indicated that the effect of this surfactant was not clearly predictable. In the present experiments we therefore had some hope of finding filter media or combinations that would be affected less adversely than glass.

All these runs were made using JP-5 containing 0.1% water and 25 ppm (7 lb/100 bbl) of Santolene C, at a flow rate of 150 ml/min through the modified separometer cell. From another project, we had a reliable value for the effect of this concentration on the standard pair of fine plus coarse separometer filter discs. For this combination, in 11 runs, the surfactant lowered the WSIM from 99 $\pm$ 1 to 77 $\pm$ 4. For the customary experimental mat composed of two coarse glass discs, the meter reading was lowered from 78 $\pm$ 4 (8 runs) to about 40 (average of 6 values from 27 to 53).

The results of these tests are listed in Table 5, and the changes in index are shown in Figure 1. The table also gives the weight and pressure drop of the mats. When separate mats were used for the runs with and without Santolene C, their weights and pressure drops were averaged.

It is evident that none of the 10 plastic media tested was notably resistant to the surfactant. The reduction in index was proportional to the index for clear fuel, up to a peak at about 80; more effective glass mats were somewhat less depreciated.

TABLE 5

EFFECT OF SANITOLENE C

Mat Material	FM No.	Wt. mg	ΔP cm.	Index Clear	Index + San. C	Index Washed Mat
Glass						
Stand. fine+coarse	--	129	28.6	59[1]	77[1]	99
1 Stand. fine	--	44	15.6	82	47	--
2 Stand. coarse	--	170	5.9	78[1]	40[2]	71
Coml.A fine+coarse	443	86	13.0	82	33	82
same		211	45	91	63	86
Acrilan						
Wool	47	76	6.1	47	35	50
Fabric	48	335	5.7	35	27	38
Polyurethane						
100-pore, 3/32 in.	53	323	6.8	36	29	37
Nylon						
Cloth	16	91	61	37	26	39
Cloth, close weave	21	280	7.2	67	47	71
Polyester						
Paper	43	239	6.4	73	37[3]	39
Paper	44	323	7.3	65	34	56
Wool	45	128	5.4	78	48[3]	72
PVC						
Wool	26	273	6.4	54	30[3]	31
Cloth	29	409	38	62	36	--
Polyethylene						
Sintered fiber disc, 5/64 in.	54	628	42.5	--	18	--
Same, higher porosity	55	635	23	25	33?	--
Fiber metal						
Steel 0.1 in.	225	1950	64	83	74	84
Steel 3 x 0.04 in.	627	5547	77	24	20	--
Combination						
2 Stand. coarse +						
Nylon-1/8 in.	21	466	14.3	--	45[4]	--
Acrilan-1/8 in.	48	461	14.7	--	31	--
Polyester	45	249	17.3	--	61	--
PVC-1/8 in.	29	570	67	--	79	--
same		531	56	99	86	--
Polyethylene-5/32 in	55	761	26.0	--	63	--
Ester-nylon	45-21	541	21.5	--	60	--
Glass-ester-nylon, 1/8 in.	4-45-21	571	51	--	60	88

1. Average of many values in close agreement.
2. Average of 6 values, from 27 to 53.
3. Also one much lower value.
4. Reversing the direction of flow gave an index of 49.

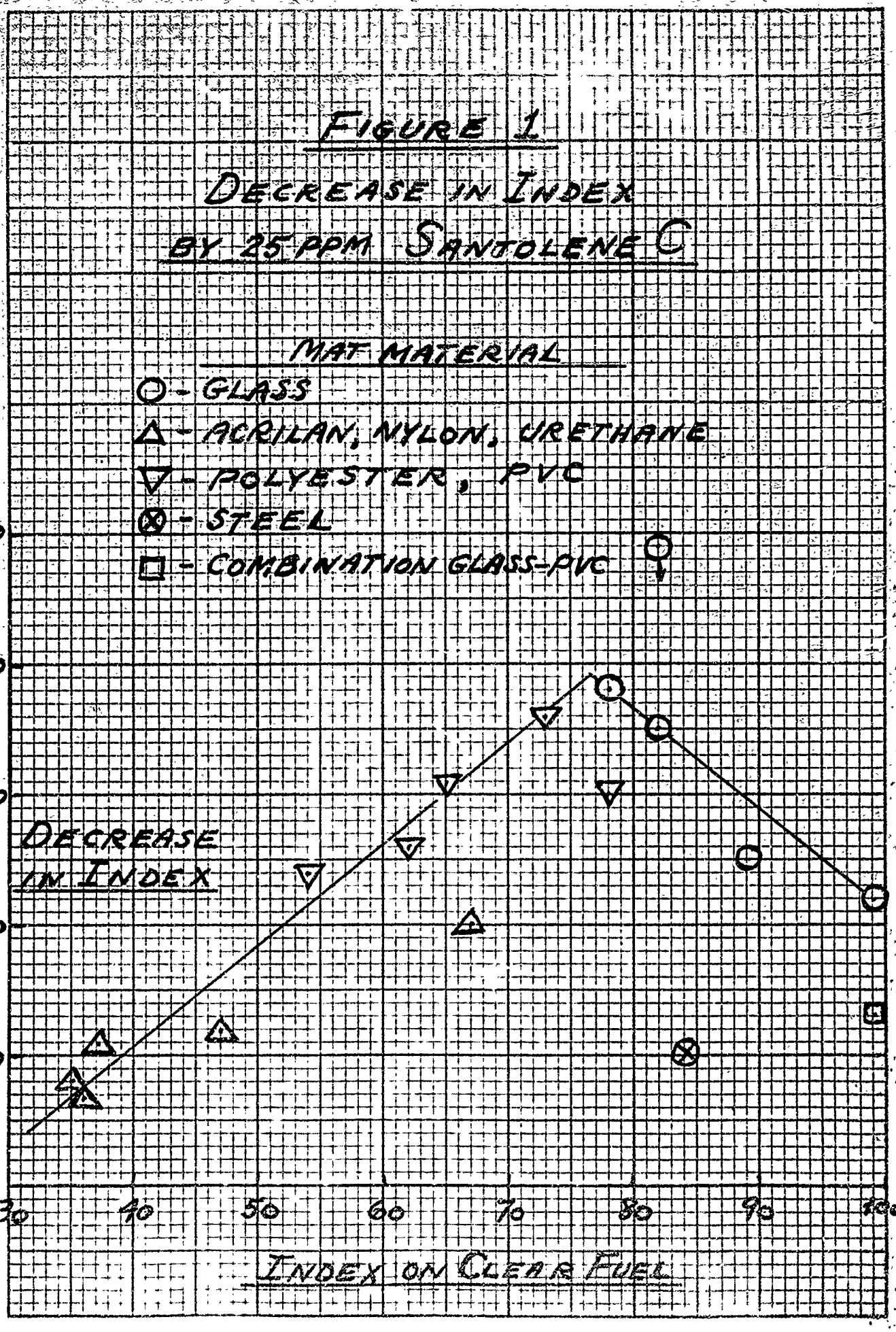


FIGURE 1
DECREASE IN INDEX
BY 25 PPM SANTOLENE C
MAT MATERIAL
○ - GLASS
△ - ACRILAN, NYLON, URETHANE
▽ - POLYESTER, PVC
⊗ - STEEL
□ - COMBINATION GLASS-PVC
DECREASE IN INDEX
0
10
20
30
40
50
30
40
50
60
70
80
90
100
INDEX ON CLEAR FUEL

Also, in most of these runs, following the test with Santolene C, the mat was washed well with isopropanol and then retested on clear fuel, to determine whether the surfactant was permanently adsorbed. These data are included in Table 5. They show that the Santolene C was strongly retained by the PVC wool and more or less so by the polyester media, but none of the other materials were permanently affected.

The combinations of glass with a downstream layer of nylon, Acrilan, or polyester were of no value. However, the combination with PVC was encouraging, attaining an index of 86 with Santolene C. This is much higher than would have been expected from an additive effect of the coarse glass (index 40) and the PVC (index 36).

Equally encouraging was the combination of coarse glass with polyethylene on the downstream side. This plastic alone had negligible coalescing action, but the combination gave an index of 63, compared with 40 for the glass alone. This is a clear-cut demonstration of synergy. It evidently results from an improvement in the collection and disengagement of the water picked up by the glass.

The initial experiment with a fibermetal mat (FM 225) appeared very promising. It led to the interesting set of experiments described in the following section.

2. Fibermetal and Wire Cloth

The first experiment that we made on a combination of filter media happened to include the effective FM 225 fibermetal disc. The mat was a sandwich of 105 mg polyurethane FM-53, 303 mg nylon FM-21, 275 mg polyester FM-45, and finally the 0.1-inch, 1950 mg steel FM 225 on the

downstream side. The result was entirely satisfactory, the index rising to 99 -- far higher than in any previous run with Santolene C in the fuel. Even increasing the water content of the JP-5 to 1% lowered the index only to 86.

Four more runs were made, using the two standard coarse glass discs followed by a metallic downstream layer. Table 6 gives the data for all these runs. For comparison, the indexes for the components taken alone are also included.

The results were extremely interesting. With the FM 225 outer layer, replacing the nylon-polyester coalescer section by the inferior coarse glass discs lowered the index of the combination mat only slightly, from 99 down to 95. Replacement of the FM 225 by FM 627 having an equal pressure drop raised the index back to 100 -- and this despite the fact that FM 627 alone has no coalescing action whatever. Finally, a single outer sheet of FM 627 was equally effective, giving an index of 100 also. It is noteworthy that this last combination had a total pressure drop 6 cm lower than that of the standard separometer pair of fine + coarse glass discs.

On the other hand, the combination with an outer layer of FM 232 wire cloth was completely ineffective -- although it had a pressure drop 40 % greater than that of the combination with a single sheet of FM 627. Since both are stainless steels, of about equal resistance to flow, it is evident that their shape or surface texture is critically important.

TABLE 6

COMBINATION MATS WITH METALLIC DOWNSTREAM LAYERS

All runs made with JP-5 + 25 ppm Santolene C under standard conditions (except for use of spacers to increase depth of coalescer cell if required).

Components Alone	Wt. mg	Δ P cm	Index
Nylon FM-21 + polyester FM-45	541	21.5	60
2 Standard coarse glass mats	170	5.9	40
Steel FM-225 0.1-in sheet	1950	64	74
3 steel FM 627 0.04-in sheets	5547	77	20[1]
Steel wire cloth FM 232	219	18.3	18 est
Combinations			
Polyurethane FM 53-nylon FM-21-Polyester FM-45 + steel FM 225, total 1/4 in.	2633	--	99[2]
2 Standard coarse glass + Steel sheet FM 225:5/32 in.	2081	73	95
Steel FM 627 - 3 sheets:7/32 in.	5766	74	100
-1 sheet:5/32 in.	1884	21.9	100
Wire cloth FM 232	370	20.5	44

1. An empty cell would show about the same index.
2. Increasing the water content to 1% lowered the index to 86.

IV. EFFECTS OF FUEL AND OPERATIONAL VARIABLES

1. Contamination by Marine Diesel Fuel

It was previously reported (GR 66-30) that a sample of marine diesel fuel, Nato Symbol F-75, gave a WSIM of only 21, indicating a high content of surface-active components (presumably of natural origin).

Addition of 10% of this diesel fuel to JP-5 lowered the WSIM from 99 + to 82-85 (2 runs). With 25 ppm Santolene C also added, the WSIM dropped from 77 for JP-5 to 53 for the contaminated fuel.

2. Addition of Antiicer

The 1st Interim Report, GR 66-1 gave WSIM data for JP-5 + 0.125% antiicer, clear and four different surfactants. The results were inconclusive with respect to the effect of the antiicer, although in the one run on clear JP-5 the WSIM was lowered from 99 to 93.

A few more runs have now been made with 0.1% antiicer. Table 7 gives the data. Again the results are far from being conclusive, but indicate that the antiicer may have little or no adverse effect.

TABLE 7

EFFECT OF ANTIICER

Coalescer mats	Santolene C ppm	Antiicer %	Index
Standard WS fine + coarse	0	0	99+
		0.1	99
	25	0	77
		0.1	98[1]
2 Standard WS coarse	0	0	78
		0.1	47[1]
	25	0	40
		0.1	31

[1] These results seem highly questionable.

3. Water Content

In Table 6 above, it was noted that an increase of water content from 0.1 to 1.0% lowered the index of a composite mat from 99 to 86, when using fuel containing Santolene C. In contrast, the standard index for clear JP-5 with 1% water is reduced only to 98.

Using inferior coalescer mats, the effect of water content becomes pronounced, as might be anticipated. For the usual test mat composed of two Standard WS discs, the index was lowered from 78 to 63 by raising the water content to 0.2% only.

4. Fuel Flow Rate

As previously reported, following the determination of an index at 150 ml/min flow rate, it has been customary to spend an additional 8 min to obtain an index at 20 ml/min. Runs made on clear JP-5 gave results in good agreement with the curve given in the previous report, GR 67-2, Figure 5. With JP-5 containing Santolene C, the increase in index on going from 150 to 20 ml/min was, on the average, slightly greater than for clear fuel.

One special experiment showed that these indexes measured at 20 ml/min represent equilibrium conditions. A mat of 2 Standard WS coarse glass discs was run on clear JP-5 at 20 ml/min from the start, for a total time of 24 min. After 15 min, the index remained unchanged at 89, a value no greater than that observed after operating at 150 ml/min.

5. Stability of the Suspension

To make visual and photographic observations of coalescence, it seemed that it might be well to use the separometer machine to prepare and pump the

water suspensions. First, however, it was necessary to ensure that the suspensions would be sufficiently stable.

A special experiment was made, in which the coalescer cell was replaced by a jumper, and the effluent fuel stream was recycled back to the reservoir. A 0.1% water suspension in clear JP-5 was prepared as usual, and was then pumped around the loop at 150 ml/min for 135 min -- a total flow of 20 liters or 10 times the original volume of fuel. The observed meter readings, plotted in Figure 2, clearly show that the suspension is very stable for a 1-hr period of pumping through a long path.

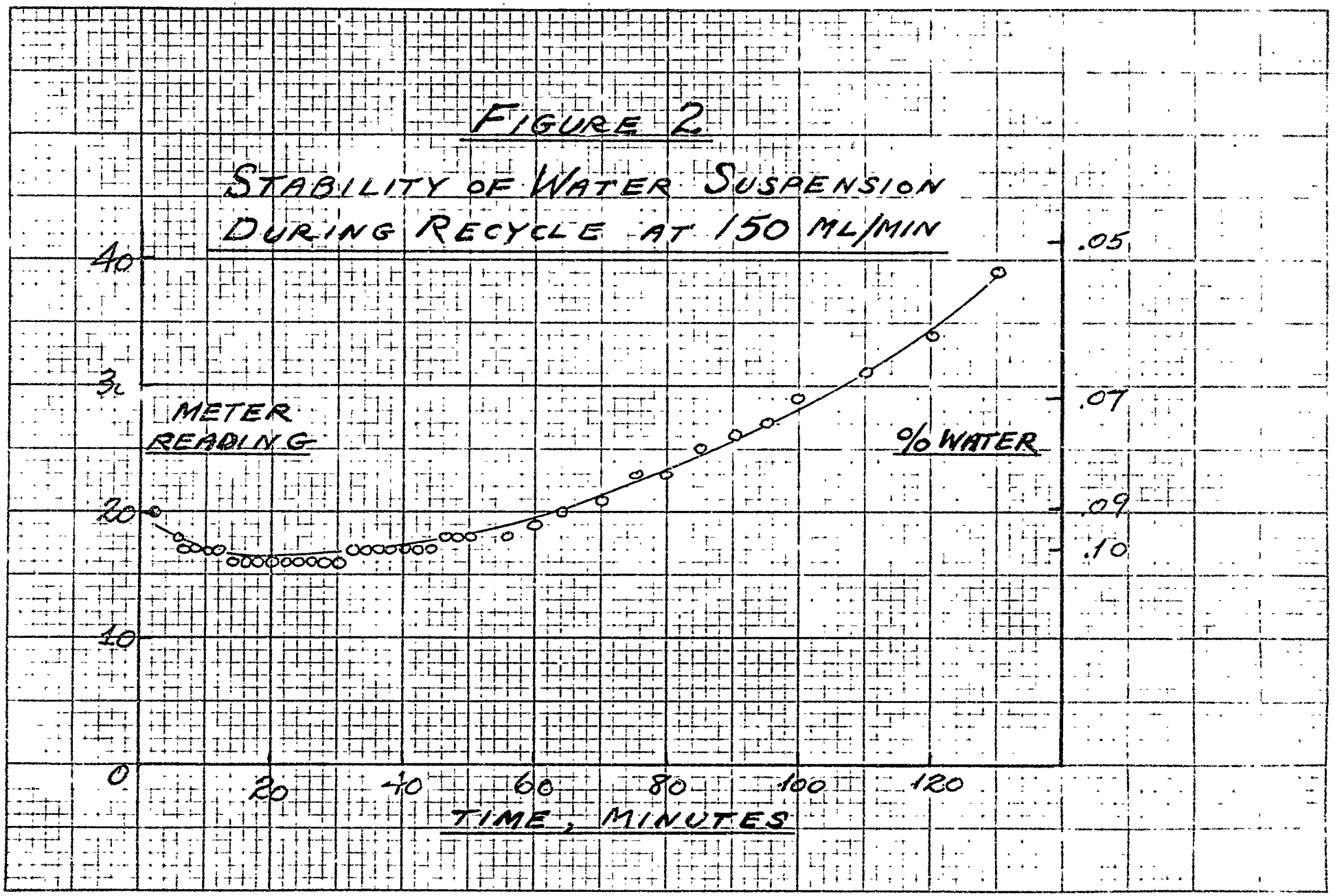


FIGURE 2.
STABILITY OF WATER SUSPENSION
DURING RECYCLE AT 150 ML/MIN
40
30
20
10
0
METER READING
.05
.07
.09
.10
% WATER
20
40
60
80
100
120
TIME, MINUTES

V. PORE SIZE AND PRESSURE DROP

1. Capillarity

The previous report, GR 67-2, described the technique used for estimation of pore sizes from rate of capillary rise. Three additional measurements were made on flat strips of polyethylene filter material, polyvinylchloride cloth, and steel fibermetal. The latter two were the same materials successfully used as downstream layers in combination mats; the polyethylene used in the combination mat was not available in strip form, but the sample tested for capillary rise was similar, though of lower porosity.

The results were not too satisfactory, in that the plots of dh^2/dt vs. h did not give well defined straight lines, and the maximum value of h was correspondingly uncertain. However, it seems clear that the plastic strips have a porosity similar to the glass mats and nylon cloth previously examined, whereas the steel has distinctly smaller pores. Table 8 gives the calculated data.

TABLE 8

PORE SIZES COMPUTED FROM RATE OF CAPILLARY RISE

Expt. No.	Material	Packing density g/cm³	Rate constants[1] a	Rate constants[1] b	h_{max} est., cm	Calcd. pore radius, microns R_1	Calcd. pore radius, microns R_2	Calcd. pore radius, microns R_{avg}
7, 8	Steel FM 627	3.61	0.122	0.0044	28	7	56	23
9	Polyethylene FM 54	0.596	.071	.0072	9.8	13	13	67
10	PVC FM 29	0.485	.161	.0133	12.1	14	143	54

[1] Constants of the straight line, $dh^2/dt = a - bh$.

2. Pressure Drop

The preceding tables of separometer index data also give the weights and pressure drops of the various mats. The packing density can be obtained from the mat weight divided by the cell volume, 0.843 cc.

For the Standard WS glass mats alone or in combination, further experience dictates small changes in the pressure drop data reported in GR 67-2, page 16. The presently accepted best average values are given in Table 9. The ΔP of the combination mat is seen to be midway between the values for the pairs of each component.

Table 9 also gives data for mats in the cell whose depth had been increased by insertion of spacers. These data will be evaluated in Part II.

TABLE 9

PRESSURE DROP OF STANDARD GLASS MATS

In cm. of water for 8 lit/min air flow in the unmodified separometer cell.

Depth of cell, in.	Number of mats	Packing density g/cm^3	Δ P, cm	No. of detns.
1/16	1 coarse (85 mg)	0.101	2.2	2
	2 "	.202	5.9 ± 0.5	27
	3 "	.303	11.0	1
	1 fine (44 mg)	.052	17.0	6
	2 "	.104	52.4	1
	1 fine + 1 coarse	.153	29.7 ± 1.5	28
1/8	1 coarse	.050	1.8	2
	2 "	.101	4.5	1
	1 coarse + 1 fine	.076	21.9	2
5/32	1 coarse	.040	1.65	2
	2 "	.081	4.0	1
	1 coarse + 1 fine	.061	18.7	1
7/32	1 coarse	.029	1.6	2
	2 "	.058	3.5	1
	1 coarse + 1 fine	.044	16.4	1

VI. VISUAL AND PHOTOGRAPHIC OBSERVATION

The initial objective of this phase of the program is to obtain a detailed view of the formation and separation of water drops at the downstream surface of a mat. It may prove useful to find out how these processes are affected by mat surface structure and by surfactants in the fuel.

To view the processes occurring in the interior of a mat is far more difficult, and will be deferred for a time. When a mat is contained by a transparent wall, one sees only the structure at the immediate vicinity of the wall and there is no assurance that the fluid flow at that point is representative of that occurring in the interior.

Preliminary visual observations of the downstream surface have been made with small mats mounted on the end of a fuel delivery tube. This is submerged in fuel contained in the observation cell described in Report GR 66-30, Figure 1. The outer layer of the mat is somewhat curved and is viewed along a tangent line, so that only a small area is in the line of sight of the microscope. A magnification of 40 x appears to be the most satisfactory. The fuel is Bayol 35 containing 0.05% of water dyed red; the dye distinguishes the water drops from the occasional bubbles of air. The concentration of water was selected by trial, to give the best view.

The separometer is used to prepare and pump the suspension, and the effluent from the observation cell is recycled directly to the fuel reservoir. As shown above, the suspension remains stable for an hour. The flow rate can readily be varied over a wide range, or can be momentarily halted.

A few photographs have been taken using a 1/600-sec flash lamp; no attempt to take motion pictures has yet been made.

We are now ready to make a short series of visual observations of different surface materials, with and without Santolene C in the fuel. It is hoped that by the time of the next report satisfactory experimental conditions will have been established and some significant results obtained.

PART II - THEORY AND DISCUSSION OF RESULTS

I. STRUCTURE AND PROPERTIES OF COALESCER MATS

1. Capillarity and Flow Resistance

It is now clear that both coalescence and disengagement of water are governed to a major degree by the structure or geometry of the coalescer mats. It is therefore important to have means of characterizing the different mat structures.

What might be called the " gross structure" is determined by the readily observable properties -- depth of mat, packing density, fiber diameter or cell wall thickness, and general form. The last term distinguishes different types of structure, such as random wool-like arrays of filaments (like fiber-glass), partly or wholly oriented fibers (paper, felt, and bundles), woven fabrics and screens, cellular foams, etc.

A description of the gross structure is useful as a means of broad classification. However, it is insufficient to predict the performance of materials such as fibrous mats and fabrics. For these, a closer view of the "micro structure" is required. This is not readily obtained by direct observation. It may, however, be deduced from measurement of capillarity and resistance to fluid flow. (Other measurable properties such as permeability to solids might also be useful, but have not been investigated in the present work.)

The capillary rise measurements reported in Part I and in Report GR 67-2 failed to provide a clear-cut definition of the micro structure, in relation to the gross structure parameters. However, the data suffice to indicate that:

(1) the size of the channels or pores in a given mat varies widely, perhaps over a 5-fold to 15-fold range; (2) all the eight mats examined had pore sizes of the same order of magnitude, although the nylon FM-21 fabric and steel fibermetal FM 627 sheet were distinctly smaller in size than the other materials.

Flow resistance is readily and accurately measurable, and should be closely related to micro structure. No special study of this subject has been made, but the data obtained in passing are sufficient for at least a preliminary analysis. For the standard glass mats used in the separometer, the data given in Part I, Table 9, cover a range of mat thickness, packing density, and fiber diameter.

For the coarse glass mats in the different depths of cell, the pressure drops are accurately correlated by the relation $\Delta P = W_c[15.7 + (1.16 + 87.4\ W_c)/V]$ where W_c is the coarse mat weight in grams and V is the cell volume in cubic centimeters (1/16 in. depth = 0.843 cc). For the fine mats, the relation is $\Delta P = W_f\,(237 + 3570\ W_f/V)$, where W_f is the weight of fine glass. For the combination fine plus coarse glass mats, ΔP is the sum of the values computed separately, allowing half the total volume for each component.

It was anticipated that there might be a simple relationship between the flow resistance of the fine and coarse fibers, but this evidently is not the case. The ratio of the fiber diameters is approximately 1 to 4, so that for equal weights, the fine mats have about 4 times the surface area and 16 times the total length of fiber. But for equal weights in a given volume, the above formulas give a ratio of the flow resistances varying from 15 to 1 up to

41 to 1, as the packing density varies from zero to infinity; at a typical density of 0.1 g/cc, the ratio is 23 to 1.

Thus in general it appears that, in flow resistance, the fiber mats are intermediate in character between screens and capillary channels, and that the degree of resistance varies with both the diameter of the fibers and the average distances between them.

2. Pore Size Distribution Theory

A paper by A. G. Ogston on "The Spaces in a Uniform Random Suspension of Fibers", Trans. Faraday Soc. 54, 1754 (1958) was reviewed. It provides a good basis for considering the effects of variables on pore size in fibrous coalescer mats. Ogston assumes a random 3-dimensional array of long straight fibers of finite length. These fibers form the bars of a series of rigid cages or "spaces" of different sizes. The size of each space is defined by the radius of the largest sphere that can be confined within it. For the simplified case where the fibers are long enough to ignore end effects, and have negligible diameter, the probability distribution function of the sizes is given by $dP/dy = 2ye^{-y^2}$, where P is probability, $\int_0^\infty dP = 1$, $y = r\sqrt{2\pi L}$, r = size of space, and L = average total length of fiber per unit volume of mat.

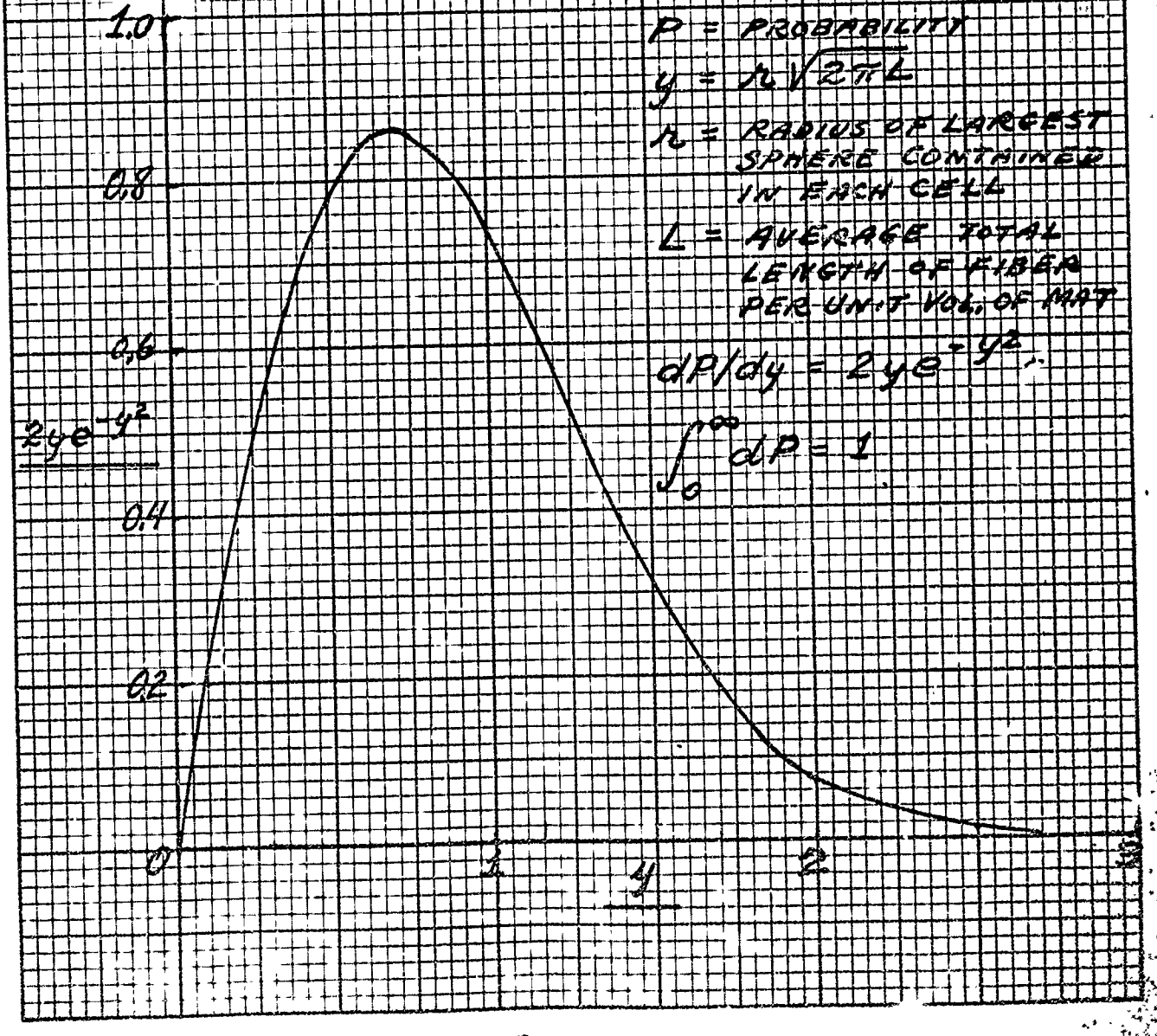
Figure 3 shows a plot of the distribution function against y. It is seen that the modal value of y is $\sqrt{1/2}$, and that there are practically no spaces more than three times as large as the mode. Nor are there many very small spaces.

In a closely packed mat, the diameter of the fiber becomes significant. As long as the thickness is not sufficient in relation to the concentration L

for the fibers to interfere significantly with each other's random distribution or orientation, the correction is simple: the average radius of the fiber is substracted from r as defined above. Since $L = 4V/\pi D^2$, where V is the fraction of total volume occupied by fibers of average diameter D, it follows that the corrected value of space radius, R, is given by $R = D\,(y\sqrt{1/8V} - 1/2)$. The modal value of R is then equal to $D(1/4\sqrt{1/V} - 1/2)$. (At high values of V, above perhaps 10 or 20%, this model is clearly no longer valid.)

FIGURE 3

DISTRIBUTION FUNCTION FOR CELL SIZE IN A RANDOM MAT OF FIBERS



P = PROBABILITY

$y = r\sqrt{2\pi L}$

r = RADIUS OF LARGEST SPHERE CONTAINED IN EACH CELL

L = AVERAGE TOTAL LENGTH OF FIBER PER UNIT VOL. OF MAT

$dP/dy = 2ye^{-y^2}$ ∴

$\int_0^\infty dP = 1$ ∴

Figure 4 gives a plot of this linear relation for typical values of V. For the fine fiberglass layers in filter/coalescer elements, V is customarily in the range from 2 to 5% and D varies from 1 to 5 μ, with an average value of about 3.5 μ. For the coarse glass layers in the various elements we have examined, V ranges from 8 to 12%; D varies widely, generally from 5 to 20 μ or more, with an average of about 15 μ. These ranges are indicated by the shaded areas in Figure 4. Assuming that the theoretical model is a more or less valid representation of actual fiber mats, it is evident that the typical fine and coarse layers taken from commercial elements do not differ greatly in cage size.

However, it is certain that these theoretical modal space sizes are numerically much smaller than the actual values of average capillary pore radius, as determined by the rate of capillary rise. This indicates that the fibers in an actual mat are not in a completely random array, but are to some degree bunched together. The application of the resin coating on the glass fibers is no doubt partly responsible for this.

Nevertheless, it appears that Figure 4 is qualitatively valid. Then, even in a mat of high voids content (low value of V), an array of fine fibers must effect a screening action or squeeze on even small water droplets. This enforced contact must be largely responsible for droplet adherence on the fibers, for we have previously shown (Report GR 66-30) that droplets have very little tendency to adhere on impact with a single fiber. The initial adherence of droplets of a fiber will greatly increase its effective diameter, thereby reducing the apparent pore size still further and facilitating coalescence between free and attached droplets.

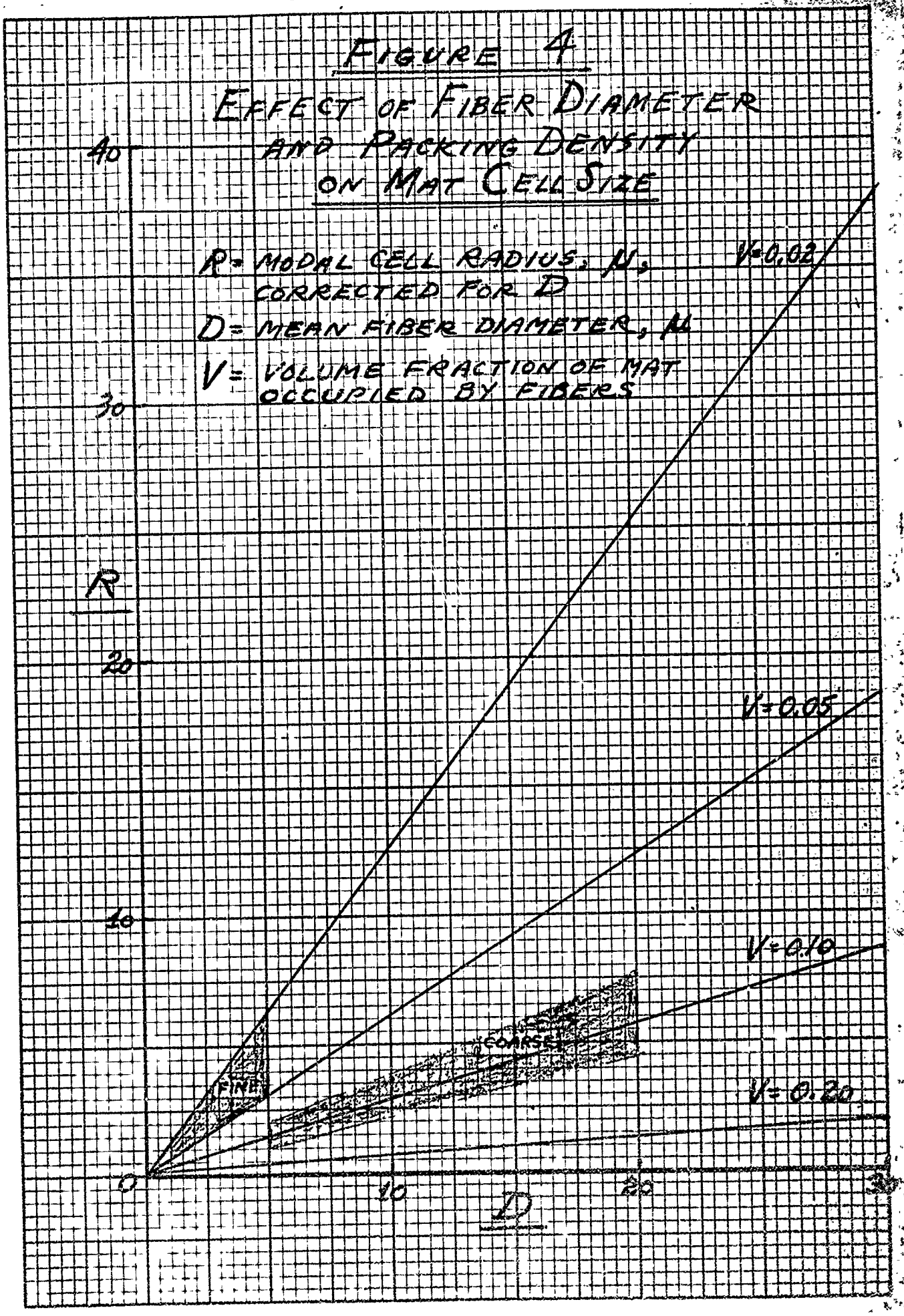
FIGURE 4

EFFECT OF FIBER DIAMETER AND PACKING DENSITY ON MAT CELL SIZE

R = MODAL CELL RADIUS, μ, CORRECTED FOR D

D = MEAN FIBER DIAMETER, μ

V = VOLUME FRACTION OF MAT OCCUPIED BY FIBERS



II. PERFORMANCE OF COALESCER MATS

1. Correlation of Mat Structure and Separometer Index

Attempts to obtain useful correlations have only served to show that the coalescence process is complex and not readily predictable. Even for a given material (coated glass) in a fixed cell volume, tested at a constant fuel flow rate and water content, there is no clear-cut relation between the index and the packing density and fiber diameter.

In Table 2 are indexes for 11 individual mats of Standard WS, Coml. A, and Coml. B2 fine or coarse glass at various packing densities in the standard 1/16 inch cell. Average fiber diameters and densities of each glass were estimated, and the lengths and surface areas of each packing were computed. These data are given in Table 10. The best correlation was between the index and the theoretical modal radius of the interfiber spaces, obtained as shown in Figure 4 above. The index is in linear inverse proportion to R, being approximately equal to 107 -7.5 R (where R is in microns), as illustrated in Figure 5.

As will be seen, the correlation is surprisingly good (considering the uncertainty in the values of the average fiber diameter D), but there is one conspicuous exception: the index for the single Standard WS coarse mat is far higher than predicted. Yet its rating was confirmed by three separate runs, and there is no evident explanation for its exceptional merit.

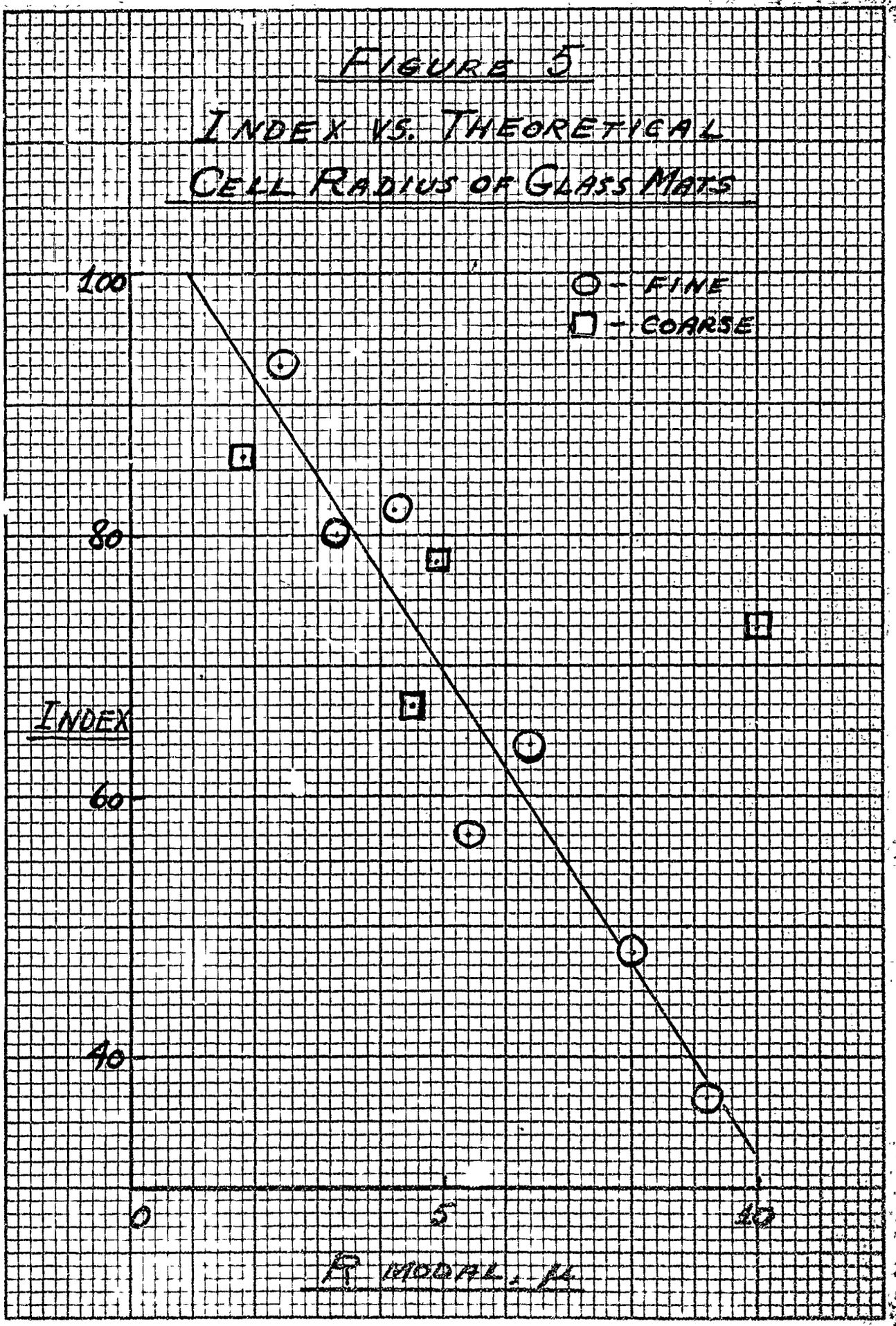
TABLE 10

INDEX AND DIMENSIONS OF SINGLE GLASS MATS

Material	Est. average D, μ	Est. average ρ	Wt. mg	ΔP cm	Index	Packing dens. g/cc	Packing V, %	Fiber area cm^2	Fiber length meters	Theor. modal R, μ
Fine fibers										
Standard WS	4	2.0	18	5.9	48	0.021	1.1	90	720	8.0
			44	17.0	82	.052	2.6	220	1750	4.2
			88	52.5	93	.104	5.2	440	3500	2.4
Coml. A	4	2.0	30	7.2	57	.036	1.8	150	1200	5.4
			60	-	80	.072	3.6	300	2400	3.3
Coml. B-2	4	2.0	13	2.3	37	.016	0.8	65	520	9.2
			23	7.1	64	.027	1.4	115	920	6.4
Coarse fibers										
Standard WS	15	2.2	85	2.1	73	.101	4.6	103	220	10.0
			170	5.9	78	.202	9.2	206	440	4.9
Coml. A	18	2.2	301	7.0	86	.357	17.0	304	540	1.9
Coml. B-2	25	2.2	253	6.8	67	.300	13.5	184	230	4.5

FIGURE 5

INDEX VS. THEORETICAL CELL RADIUS OF GLASS MATS



2. Mat Thickness and Residence Time

For the standard 1/16-inch coalescer cell, the relation between the index and the fuel flow rate was shown in the previous report GR 67-2, Figures 5 and 6. The increase in residence time obtained by a decrease in flow rate raises the index somewhat, as might be expected. The index was likewise raised by an increase in residence time, when this was obtained by enlarging the thickness of the cell, for a given weight of mat.

The latter, however, reduces the packing density and -- according to the above correlation -- this should reduce the efficiency of the mat more than enough to offset the improvement in residence time. The fact that it does not do so implies that mat thickness in itself is an important factor. Why this should be so is not at all evident.

It would have been instructive -- and perhaps profitable -- to have made a much more thorough and detailed study of the interrelated effects of all these structure and operating variables for individual coated glass mats. However, it appeared that, from a practical point of view, these effects would be subordinate to the more important effects obtained by using different materials and, more particularly, combinations thereof.

3. Materials of Construction

It has always been tacitly assumed that the chemical nature of the fiber surface is an important factor in determining its performance. For reliable evaluation of different materials, it is evident that they should be compared in mats having similar structural parameters. This can now be done, at least to an approximate degree, for wool-like mats of fibers in the 5-40 μ

range. Table 11 lists the indexes of such mats, for fuel both clear and with Santolene C. It is evident that there is indeed a wide variation in performance of different surface materials, with resin-coated glass and polyester being the best, and nylon and steel the poorest.

The table also lists the previously-determined values of the contact angles of water on these surfaces, when submerged in fuel. It is obvious that there is no observable correlation whatever between these values and the indexes. Nor is there any evident relation of the indexes to the previous observations of droplet adherence and detachment for single filaments.

TABLE 11

PERFORMANCE OF MATS OF SIMILAR STRUCTURE

Material	FM No.	Contact angle deg.	D, μ	Wt. mg	ΔP cm.	Index Clear + San. C	
Polyester	45	-	15	128	5.4	78	48
Phenolic resin on glass (2 St. coarse)	-	110	5-20	170	5.9	78	40
Glass uncoated	1	50	3-8	142	7.3	66	-
Cotton	5	-	15-40	150	6.4	60	-
PVC	26	145	37-40	273	6.4	54	30
Acrilan	47	-	5-20	76	6.1	47	35
Steel	236	115	10	463	6.0	37	-
Nylon	49	86	10-14	106	7.3	35	-

Another significant fact to be considered is the outstanding performance of the steel fibermetal FM 225 sheet (index = 83), in comparison with the well-high complete lack of coalescence of other fibermetal sheets and steel wire

cloth (Table 4). There is nothing in the manufacturer's specifications (Table 1) that would distinguish the FM 225 from the other sheets.

From this array of evidence, one is led to conclude that there are indeed marked differences in performance of mats of approximately similar gross structure -- but that these differences are the result of subtle variations in surface properties that have not yet been identified.

4. Combination Mats

As previously shown (Table 2), the combination of Standard WS fine and coarse mats is distinctly superior to an equal amount of either one alone, provided the coarse layer is on the downstream side. Although this fact has been well recognized in the design of filter/coalescer elements, there has been no satisfactory explanation of it.

Only a few other combinations have been tested with clear fuel (Table 3). Most of the limited investigation to date has been with fuel containing Santolene C, discussed in the following section. However, the final run listed in Table 3 is noteworthy. Here, a downstream layer of PVC FM 29 raised the index of two Standard WS coarse mats from 78 to 99. Since the PVC alone was quite effective (index = 62), one cannot be positive that the combination exhibited synergy, but it seems almost certain that it did so.

In general, it appears that we are dealing with two separate processes -- one, the coalescence of the influx droplets on the fiber surfaces or on attached water; the other, the transport of the bulk water through the mat and its disengagement at the downstream surface. And it appears that these processes have different optimum mat structures. If valid, this conclusion offers encouraging possibilities for the development of improved filter/coalescer elements.

5. The Effect of Surfactants

The following remarks are limited to JP-5 fuel containing Santolene C, since the effects of other additives have not yet been investigated in detail. The previous studies made on single fibers indicated that surfactant effects are highly specific. It is therefore possible that very powerful surfactants, such as the sulfonates, will have a mode of action in a coalescer mat that is different from that of the corrosion inhibitors. This will be determined later.

It was somewhat unexpected to find that all materials (except the steel FM 225) were more or less equally affected by Santolene C (Table 5 and Figure 1). It may well be that the principal site of its action is at the water-fuel interface. Here the formation of a film on the water and consequent lowering in interfacial tension may facilitate the displacement of the attached drops and their expulsion from the mat. This would reduce the opportunity for their coalescence with droplets in the inflowing fuel. It would also tend to reduce the size of the drops delivered to the down-stream surface.

However, there must also be some specific effects on the surface of the fibers. This is clearly evidenced by the strong adsorption of the surfactant on some of the materials (polyester and PVC) and continued low index in subsequent operation with clear fuel.

The remarkable benefits obtained in some of the combination mats were much greater than anticipated. The essential fact is that it was possible to obtain an index of 100 on Santolene C fuel, with a mat having a lower pressure drop than the standard pair of glass mats which gave an index of 77. This successful combination would not be practical, since the fibermetal sheet

would be hopelessly expensive. Regardless of this, the fact that it works is indeed very promising. And the fact that a downstream layer of an inert, low-energy material like polyethylene also had a large effect shows that steel is not unique in this respect.

CONCLUSIONS AND RECOMMENDATIONS

Specific conclusions drawn from the various experimental results are embodied in the preceding discussion in Part II. From these and previous results, several general conclusions of importance are as follows:

1. Knowledge of basic chemical parameters (compositions of fuels and mats, interfacial tensions, adsorption, etc.), while doubtless relevant, will not provide a solution of the problem. In particular, it does not appear likely that a useful mat material can be found that will be wholly unaffected by surfactants.

2. The effects of fuel flow rate and water content are much the same for different fuels and coalescer mats, and are therefore not a critical factor in the development of improved mats.

3. The composition and structure of the mat itself is all-important. Chemical composition may not be nearly as important as surface texture. Fiber diameter, pore size, and mat thickness are major factors.

4. The overall process involves several distinct steps: attachment of water droplets to solid surfaces, coalescence of free droplets with attached water, coalescence of neighboring masses of attached water, transport of coalesced water through the mats, and finally aggregation and disengagement of the transported water at the downstream surface.

5. Because of this succession of steps, combination mats of different layers may be much more effective than single layers of equivalent flow resistance. Composite mats of different materials in intimate mixture remain to be tested.

6. In particular, the effect of Santolene C in the fuel can be overcome by the synergistic action of a suitable combination. Whether this is also true for a different kind of surfactant such as Aerosol OT remains to be determined.

7. The nature or structure of an effective outer layer in a combination has not yet been defined. On very limited evidence, it appears that this layer should be somewhat hydrophobic and should comprise a plurality of lengthy, tortuous passages of relatively large diameter.

For the immediate future program, emphasis in general will be on the development of effective combinations that might be practicable for commercial use. Some specific areas to be investigated are the following:

1. Visual and photographic observations of the downstream surface, and possibly of the interior structure. If initial efforts do not appear rewarding, this area will be abandoned.

2. Comparison of Aerosol OT with Santolene C in a good combination mat.

3. Comparison of a few of the previous experimental mats with the same materials in a cell of greater depth and greater effective area (and hence lower linear fuel flow rate), and with higher water content in the fuel -- so as to simulate more closely the conditions in a commercial element.

4. Preparation of a few composite mats of mixed materials, for comparison with the same materials in separate layers. Hopefully this can be done by chopping wool-type materials into short lengths and depositing both mixtures and separate layers of these on wire cloth or fabric.

5. Investigation of the effect of surface texture in fibers of similar size and composition. It should be possible to pr. cure stainless steel and possibly polyethylene with both smooth and rough surfaces in loose, unsintered form.

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13. ABSTRACT Removal of 0.1% suspended water in JP-5 fuel was measured in a separometer using a variety of glass, synthetic, and metallic fiber mats. Addition of 25 ppm Santolene C corrosion inhibitor lowered the WSIM from 99 to 77 ± 4, and had more or less adverse effect on all materials examined. It was discovered that this adversity could be overcome by using a 2-layer combination of fiberglass upstream and fibermetal downstream. The glass alone gave an index of 40; the metal had no coalescing action at all (index = 20); the combination gave an index of 100. The pressure drop across the combination was low. A downstream layer of sintered polyethylene fiber had a similar but less pronounced synergistic effect. In clear JP-5, addition of 10% of marine diesel fuel lowered the WSIM to 84; 0.1% antiicer apparently had little or no effect. For glass mats, the variation in index and pressure drop with fiber diameter, packing density, cell depth, and fuel flow rate and water content was observed.

14. KEYWORDS

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